REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
12-06-2008	Final	

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
CONTROL OF AIR VEHICLE SWARMS	F49620-02-1-0388
	5b. GRANT NUMBER AFOSR
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Dr. Raffaello D'Andrea	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Sibley School of Mechanical and Aerospace Engineering Cornell University Ithaca, NY 14853	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NL 875 Randolph Arlington VA 22203	10. SPONSOR/MONITOR'S ACRONYM(S) AFOSR
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-SR-AR-TR-08-0346

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution A: Approved for Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This program addressed the coordinated control of clusters and swarms of uninhabited aerial vehicles (UAVs). UAVs have been identified as key elements in future military systems. In particular, they offer the ability to perform tasks that cannot be achieved with aircraft directly piloted by human beings (due to size and maneuverability constraints). In addition, if they can be constructed for a low enough cost, they can be treated as expendable assets, greatly increasing their tactical potential. One scenario for the deployment of UAVs is in clusters and swarms. Such a deployment will increase their effectiveness through cooperation of distributed resources, robustness to individual vehicle failure and neutralization, and by performing tasks that only spatially distributed vehicles can achieve. Our main objective was a comprehensive program aimed at developing the tools and techniques required for the effective deployment of UAV swarms. We brought to bear the most promising results in the area of multi-vehicle control - here at Cornell, at other institutions, and at government labs - and applied them to two bench-mark experiments: the control of a large number of UAVs that implement a dynamic, phased array antenna, and the coordinated control of a large number of ground vehicles.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18
Adobe Professional 7.0

20101014471

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DTIC Data

Purchase Request Number:	FQ8671-0600899
BPN:	F1ATA06024B899
Proposal Number:	02-NM-159
Research Title:	(PECASE-02) CONTROL OF AIR VEHICLE SWARMS
Type Submission:	
Inst. Control Number:	F49620-02-1-0388P00004
Institution:	CORNELL UNIVERSITY
Primary Investigator:	Mr Raffaello D'Andrea
Invention Ind:	none
Project/Task:	5094S / S
Program Manager:	William M. Mceneaney

Objective:

To develop comprehensive theory, tools and techniques for deployment and coordinated control of clusters and swarms of uninhabited aerial vehicles (UAVs). One scenario for the deployment of UAVs is in clusters and swarms. Such a deployment will increase their effectiveness through cooperation of distributed resources, robustness to individual vehicle failure and neutralization and by performing tasks that only vehicles which are distributed in space can achieve. One of the main objectives is to develop new robust control algorithms for controlling large numbers of UAVs, with the emphasis being on distributed and hierarchical control synthesis and analysis tools. The PI will include exploring the role of human-in-the-loop control of vehicle swarms.

Approach:

The PI will bring to bear the most promising results in the area of multi-vehicle control and apply them to two bench-mark experiments: the control of a large number of UAVs that implement a dynamic, phased array antenna, and the coordinated control of a large number of ground vehicles. These bench-mark experiments will serve as excellent test-beds for applying robust and optimal control techniques to aggressive vehicle control, and for extending theses tools to multi-vehicle swarms where cooperation must be achieved in a dynamic, communication limited environment. The research effort will be coordinate with work on mixed initiative control of automa teams. The PI will begin by constructing one UAV and designing robust and optimal controllers that will give the UAV the ability to maneuver aggressively. Based on high fidelity models of the UAV, a suite of models for the UAV phased array antenna will be constructed. Previously funded research on ground based cooperative vehicle teams will be leveraged for the second testbed.

Progress:

Year: 2004 **Month:** 10

ANNUAL REPORT FOR: F49620-02-1-0388

We implementated a joint Cornell-Caltech summer program where a group of six undergraduate students worked closely with graduate students, post-doctoral research associates, and one visiting assistant professor to explore human in the loop control of multi-vehicle systems using the Cornell multi-vehicle test bed. A summary, and associated software are available at roboflag.mae.cornell.edu.

We are continuing research on using clusters of UAVs to transmit large amounts of data by forming a Phased Array Antenna (PAA) . We have investigated the feasibality of this method and compared it to some alternative, simpler approaches. In particular, we first found a figure of merit for the system (the link quality) , computed this for the several possible UAV phased array cases, determined how the alternative apporaches affect the link quality, and then compared the performance of all approaches.

Progress:

Year: 2004 **Month:**

ANNUAL REPORT F49620-02-1-0388

This program addresses the coordinated control of clusters and swarms of uninhabited aerial vehicles (UAVs). UAVs have been identified as key elements in future military systems. In particular, they offer the ability to perform tasks that cannot be achieved with aircraft directly piloted by human beings (due to size and maneuverability constraints). In addition, if they can be constructed for a low enough cost, they can be treated as expendable assets, greatly increasing their tactical potential. One scenario for the deployment of UAVs is in clusters and swarms. Such a deployment will increase their effectiveness through cooperation of distributed resources, robustness to individual vehicle failure and neutralization, and by performing tasks that only spatially distributed vehicles can achieve.
Our main objective is a comprehensive program aimed at developing the tools and techniques required for the effective deployment of UAV swarms. We are bringing to bear the most promising results in the area of multi-vehicle control - here at Cornell, at other institutions, and at government labs - and applying them to two bench-mark experiments: the control of a large number of UAVs that implement a dynamic, phased array antenna, and the coordinated control of a large number of ground vehicles.

Year: 2005 **Month:** 11

NOT required AT this TIME.

Year: 2006 **Month:** 07

We implemented a joint Cornell-Caltech summer program where a group of six undergraduate students worked closely with graduate students, post-doctoral research associates, and one visiting assistant professor to explore human in the loop control of multi-vehicle systems using the Cornell multi-vehicle test-bed. A summary, and associated software, are available at roboflag.mae.cornell.edu. We are continuing research on using clusters of UAVs to transmit large amounts of data by forming a Phased Array Antenna (PAA). We have investigated the feasibility of this method and compared it to some alternative, simpler approaches. In particular, we first found a figure of merit for the system (the link quality), computed this for the several possible UAV phased array cases, determined how the alternative approaches affect the link quality, and then compared the performance of all the approaches.

We have completed the hardware design of the Cornell autonomous flying vehicle (AFV). We have integrated an indoor GPS system from Arc Second to the vehicle design. See Figure 1.

Year: 2008 **Month:** 06 **Final**

This program addressed the coordinated control of clusters and swarms of uninhabited aerial vehicles (UAVs). UAVs have been identi♀ed as key elements in future military systems. In particular, they o♂er the ability to perform tasks that cannot be achieved with aircraft directly piloted by human beings (due to size and maneuverability constraints). In addition, if they can be constructed for a low enough cost, they can be treated as expendable assets, greatly increasing their tactical potential.
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Our main objective was a comprehensive program aimed at developing the tools and techniques required for the e♂ective deployment of UAV swarms. We brought to bear the most promising results in the area of multi-vehicle control { here at Cornell, at other institutions, and at government labs { and applied them to two bench-mark experiments: the control of a large number of UAVs that implement a dynamic, phased array antenna, and the coordinated control of a large number of ground vehicles.

CONTROL OF AIR VEHICLE SWARMS

F49620-02-1-0388

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Abstract
This program addressed the coordinated control of clusters and swarms of uninhabited aerial vehicles (UAVs). UAVs have been identified as key elements in future military systems. In particular, they offer the ability to perform tasks that cannot be achieved with aircraft directly piloted by human beings (due to size and maneuverability constraints). In addition, if they can be constructed for a low enough cost, they can be treated as expendable assets, greatly increasing their tactical potential. One scenario for the deployment of UAVs is in clusters and swarms. Such a deployment will increase their effectiveness through cooperation of distributed resources, robustness to individual vehicle failure and neutralization, and by performing tasks that only spatially distributed vehicles can achieve.
Our main objective was a comprehensive program aimed at developing the tools and techniques required for the effective deployment of UAV swarms. We brought to bear the most promising results in the area of multi-vehicle control – here at Cornell, at other institutions, and at government labs – and applied them to two bench-mark experiments: the control of a large number of UAVs that implement a dynamic, phased array antenna, and the coordinated control of a large number of ground vehicles.

Achieved Objectives

1. The transition of recent advances in robust and optimal control to single UAVs. Even though these new tools and techniques are potentially extremely powerful, and a substantial amount of research effort has been expended in developing them, there has been a correspondingly small amount of effort to transition them to real-world applications. Being a major contributor in this research area and having substantial hardware expertise has allowed our research group to effectively apply these tools to real systems, not only resulting in a benefit to military applications, but also to commercial ones.

2. Controlling large numbers of UAVs will require distributed computation and control; purely centralized control is not feasible to implement, is difficult to design, and is not robust to centralized failures. One of our main objectives was to develop new control algorithms for controlling large numbers of UAVs. Our emphasis was on developing distributed and hierarchical control synthesis and analysis tools. Results have

Figure 1: Cornell AFV

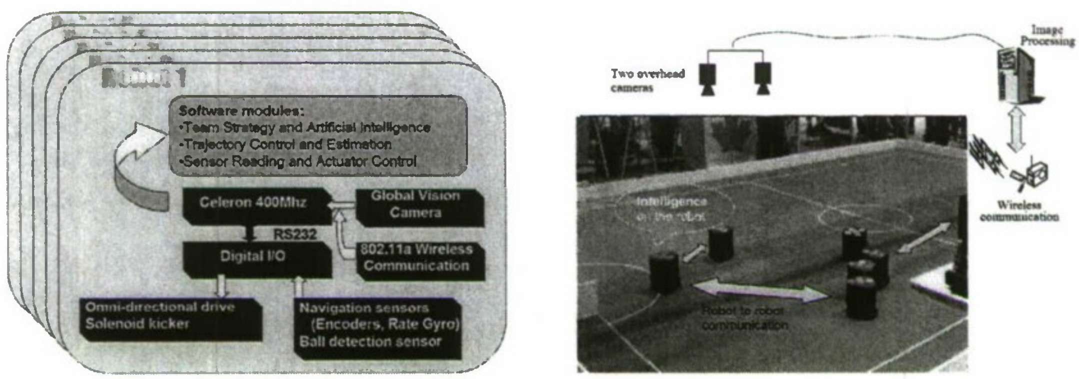

Figure 2: Cornell Mobile Robots

shown that these new control design techniques based on semidefinite optimization can yield tractable conditions which yield distributed controllers, and naturally lend themselves to distributed implementation with limited inter-vehicle communication.

3. The exploration of human in the loop control of vehicle swarms. Many applications of UAVs may require a human in the loop for high level decisions.

4. To use as a benchmark problem phased array antennas for high-bandwidth UAV communication. For many applications, such as SAR mapping and real-time video, there may be a need for a high data rate communications link between UAVs and a base station/satellite. It is difficult, mainly because of size restrictions, to put a high gain antenna on a UAV. We investigated whether a formation of UAVs, each carrying a low gain antenna, can form a high gain phased array.

AFRL Point of Contact
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Acknowledgment/Disclaimer
This work was sponsored (in part) by the Air Force Office of Scientific Research, USAF, under grant/contract number F49620-01-1-0119. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Air Force Office of Scientific Research or the U.S. Government.

Personnel Supported During Duration of Grant

1. Raffaello D'Andrea (PI), Associate Professor, Cornell University.
2. JinWoo Lee, Post-doctoral research associate, Cornell University.
3. Keyong Li, Post-doctoral research associate, Cornell University.
4. Eryk Nice, Graduate Student, Cornell University.
5. Oliver Purwin, Graduate Student, Cornell University.
6. Sean Breheny, Graduate Student, Cornell University.
7. Jeff Fowler, Graduate Student, Cornell University.
8. Atif Chaudhry, Graduate Student, Cornell University.
9. Dr. Julie Adams, Visiting Assistant Professor, Rochester Institute of Technology.

Publications

[1] O. Purwin and R. D'Andrea. Theory and implementation of path planning by negotiation for decentralized agents. *Robotics and Autonomous Systems*. To appear.

[2] K. Li and R. D'Andrea. Motion design and learning of autonomous robots based on primitives and heuristic cost-to-go. *Robotics and Autonomous Systems*. To appear.

[3] R. Chandra, S. Breheny, and R. D'Andrea. Antenna array synthesis with clusters of unmanned aerial vehicles. *Automatica*. To appear.

[4] J. Fowler and R. D'Andrea. Structured analysis of piecewise-linear interconnected systems. *International Journal of Robust and Nonlinear Control*, 17(18):1754–1770), 2007.

[5] O. Purwin and R. D'Andrea. Trajectory generation and control for four wheeled omnidirectional vehicles. *Robotics and Autonomous Systems*, 54:13–22, 2006.

[6] R. D'Andrea. The Cornell RoboCup Soccer Team: 1999 - 2003. In B. Levine and D. Hristu, editors, *Handbook of Networked and Embedded Control Systems*, pages 793–804. Birkhauser, 2005.

[7] J. M. Fowler and R. D'Andrea. A formation flight experiment: Constructing a test-bed for research in control of interconnected systems. *Control Systems Magazine*, 23(5):35–43, 2003.

[8] O. Purwin and R. D'Andrea. Cornell Big Red 2003. In D. Polani, A. Bonarini, B. Browning, and K. Yoshida, editors, *RoboCup 2003: Robot Soccer World Cup VII*, Lecture Notes in Computer Science. Springer, 2003.

[9] K. Li and R. D'Andrea. An order-based approach to mission-oriented autonomous robot control: Managing complexity, merging multiple plans, and performance analysis given partial probabilistic information. In *Proc. IFAC World Congress*, 2008.

[10] O. Purwin and R. D'Andrea. Path planning by negotiation for decentralized agents. In *Proc. American Control Conference*, pages 5296–5301, 2007.

[11] K. Li and R. D'Andrea. Trajectory design of autonomous vehicles based on motion primitives and heuristic cost-to-go functions. In *Proc. IEEE Conference on Decision and Control*, 2006.

[12] O. Purwin and R. D'Andrea. Trajectory generation for four wheeled omnidirectional vehicles. In *Proc. American Control Conference*, pages 4979–4984, 2005.

[13] A. Chaudhry, K. Misovec, and R. D'Andrea. Low observability path planning for an unmanned air vehicle using mixed integer linear programming. In *Proc. IEEE Conference on Decision and Control*, pages 3823–3829, 2004.

[14] M. Campbell, R. D'Andrea, J. Lee, and E. Scholte. Experimental demonstrations of semi-autonomous control. In *Proc. American Control Conference*, pages 5338 – 5343, 2004.

[15] S. Breheny, R. D'Andrea, and J. C. Miller. Using airborne vehicle-based antenna arrays to improve communications with UAV clusters. In *Conference on Decision and Control*, pages 4158–4162, 2003.

[16] R. D'Andrea and R. M. Murray. The RoboFlag competition. In *American Control Conference*, pages 650–655, 2003.

[17] R. D'Andrea and M. Babish. The RoboFlag testbed. In *American Control Conference*, pages 656 – 660, 2003.

[18] M. Campbell, R. D'Andrea, D. Schneider, A. Chaudhry, S. Waydo, J. Sullivan, J. Veverka, and A. Klochko. Roboflag games using systems based, hierarchical control. In *Proc. American Control Conference*, pages 661 – 666, 2003.

[19] R. S. Chandra, J. Fowler, and R. D'Andrea. Control of interconnected systems of finite spatial extent. *IEEE Conference on Decision and Control*, pages 238 – 239, 2002.

Transitions and Seminars

1. Tufts University, Department of Mechanical Engineering. November 2007.
2. Universidad ORT Uruguay, Montevideo, Uruguay. December 2006.
3. Massachusetts Institute of Technology, Department of Aeronautics and Astronautics, Boston, MA. May 2006.
4. ETH Zurich, Automatic Control Seminar, Switzerland. January 2006.
5. Massachusetts Institute of Technology, Laboratory for Information and Decision Systems, Boston, MA. September 2005.
6. Boston University, Electrical and Computer Engineering Department, Boston, MA. March 2005.
7. Charles Stark Draper Laboratory, Boston, MA. January 2005.
8. Tokyo Institute of Technology, Department of Control and Systems Engineering, Japan. October 2004.
9. Tokyo Denki University, System Control Seminar, Japan. October 2004.
10. ETH Zurich, Automatic Control Seminar, Switzerland. September 2004.
11. Lund University, Department of Automatic Control, Sweden. May 2004.
12. University of Pennsylvania, Mechanical Engineering and Applied Mechanics Department. November 2003.
13. Stanford University, Aerospace Engineering Department. September 2003.
14. Charles River Analytics, Boston, MA. August 2003.
15. University of Padova, Italy, Dipartimento di Ingegneria dell'Informazione. July 2003.
16. University of Illinois at Urbana, Aeronautical and Astronautical Engineering Department. April 2003.
17. Vanderbilt Electrical Engineering and Computer Science Lecture Series, Nashville, TN. November 2002.
18. The Center for Bits and Atoms, Massachusetts Institute of Technology, Boston, MA. October 2002.
19. University of Florida, Research Institute for Autonomous Precision Guided Systems, Shalimar, Florida. May 2002.
20. GRASP Laboratory, University of Pennsylvania, Philadelphia, Pennsylvania. May 2002.
21. AFOSR Workshop on Future Directions in Control, Arlington, Virginia. April 2002.

Honors and Awards

1. Cornell University Provost Award for Distinguished Scholarship. 2006.
2. RoboCup Second Place Winners, F180 League, Systems Architect and Faculty Advisor. Osaka, Japan. 2005.
3. RoboCup World Champions, F180 League, Systems Architect and Faculty Advisor. Padova, Italy. 2003.
4. RoboCup World Champions, F180 League, Systems Architect and Faculty Advisor. Fukuoka, Japan. 2002.
5. Keynote Speaker, International Conference on Robot Communication and Coordination. 2007.

6. Plenary Speaker, Northeast Control Workshop. 2007.

7. Plenary Speaker, Conference on Cellular Automata for Research and Industry. 2006.

8. Plenary Speaker, Robot Motion Control Conference. 2004.

9. Air Force Rome Laboratories Information Institute's Frontiers in Information Sciences Distinguished Lecture Series. 2004.

10. Plenary Speaker, American Control Conference. 2003.

11. Special Topic Invited Speaker, Mathematical Theory of Networks and Systems Conference. 2002.